Fermilab

SSC DETECTOR SOLENOID DESIGN NOTE #115

TITLE: External Pressure Design and Layout of Chimney for the SDC Solenoid

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DATE: October 15, 1990

ABSTRACT: This Design Note contains the design standards and specifications for the chimney, preliminary design calculations for a rectangular chimney, design calculations for a cylindrical chimney and preliminary chimney dimensions.

SUMMARY: The design calculations for both the square and the cylindrical chimney were done in accordance with Section VIII, Division 1 of the ASME Pressure Vessel Code. Design rules for the square chimney are in Appendix 13, Vessels of Noncircular Cross Section. Design rules for the circular chimney are in Part UG. ASME/ANSI B31.3, Chemical Plant and Petroleum Refinery Piping, specifies that Section VIII, Division 1 of the ASME Pressure Vessel Code be followed to determine wall thickness and stiffening requirements for straight pipe under external pressure.

The calculation for a cylindrical chimney shows that the chimney can be fabricated with 12" Schedule 10 aluminum pipe. The wall thickness is 0.18". The outside diameter is 12.75". The maximum allowable external pressure is 25.4 psi. The collapse pressure safety factor is 3.25. Circumferential stress at the collapse pressure is 890 psi.

The calculation for a square, unstayed, aluminum chimney indicates a minimum required wall thickness of 0.875" to 1". This calculation is preliminary because I have two unresolved questions about the design rules in paragraph 13-14 of Appendix 13. The questions are discussed on page 9.

A square chimney stayed at midlength may have thinner walls. No calculations were performed on this type of chimney.

CONCLUSION: At this time, a cylindrical chimney is preferred over a square one because the cylindrical design has a much smaller radiation thickness. There appears to be sufficient room in it for all the required cryogenic lines, an MLI insulated shield, the coil leads and instrumentation wiring.

The relieving capacity and vacuum conductance of this cylindrical chimney must be checked before it is chosen over the square chimney.

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SUBJECT: EXTERNAL PRESSURE DESIGN AND LAYOUT OF CHIMNEY FOR THE SDC SOLENOID

NAME: A. M. STEFANIK

DATE: 8/30/90

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DESIGN SPECIFICATIONS AND STANDARDS	AMS	
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1. MINIMIZE RADIATION THICKNESS ⇒ ALUMINUM CONSTRUCTION
2. ASME SEC VIII, DIV 1, AS DIRECTED BY ANSI B31.3.
3. MAXIMUM OUTSIDE DIMENSIONS: 12" SQUARE
4. CHIMNEY CONNECTS TO CRYOSTAT AT TOP (0°) AND RUNS STRAIGHT UP THROUGH THE DETECTOR.

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SUBJECT: SQUARE OUTER WALL

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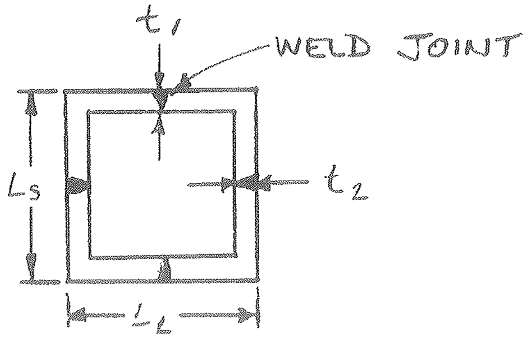
DESIGN IN ACCORDANCE WITH ASME SECTION VIII DIV 1 APP. 13

GEOMETRY #1 $L_L = L_S = 12''$; $t_L = t_S$; NO STAYS



CHIMNEY LENGTH = L_V = 35'

CHIMNEY WIDTH = H = 12"

CHIMNEY DEPTH = h = 12"

ASPECT RATIO = L_V / H = 35'/1' = 35 > 4 (13-4(h))

MATERIAL : 5083-O ALUMINUM

TABULATE ALLOWABLE STRESSES (APP 13, PARA 13-4)

$S = 9{,}800$ psi

$S_{ma_M} = S = 9{,}800$ psi IN BASE METAL

$S_{ma_W} = SE = 9{,}800\,E$ psi AT WELD JOINT

THE LONGITUDINAL JOINTS ARE CATEGORY A, TYPE NO. 2 JOINTS. CIRCUMFERENTIAL JOINTS ARE CATEGORY B OR C, TYPE NO. 2. USE FULL RADIOGRAPHIC EXAMINATION.

∴ E = 0.9 FOR ALL OF THE WELDED JOINTS. NOTE 3 OF THE JOINTS COULD BE TYPE 1.

$S_{maw} = 9{,}800(0.9) = 8{,}820$ psi

$S_{Ta} = 1.5SE = 1.5(9{,}800)(0.9) = 13{,}230$ psi

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EXTERNAL PRESSURE DESIGN REFR: APP 13, PARA 13-14 (a)(1)

$P_e = 15\ psi$

$t_1 = t_2 = t$

Assume $t = 3/8'' = 0.375''$

$S_m = PH/2t = \dfrac{15 psi\ (12 in)}{2(\quad in)}$

$= \quad psi$

$(S_b)_m = \dfrac{P_e h^2 c}{t^3}\left[-1.5 + \dfrac{(1+\alpha^2 K)}{1+K}\right]$

$c = t/2 = \quad ''/2 =$

$\alpha = H/h = 12''/12'' = 1$

$K = (I_2/I_1)\,\alpha = 1$

$(S_b)_m = \dfrac{15(12)^2(0.\quad)}{(0.\quad)^3}\left[-1.5 + \dfrac{(1+(1)(1))}{1+1}\right]$

$= \quad psi$

NOTE: THERE IS NO NEED TO FINISH THIS CALCULATION BECAUSE THE WALL THICKNESS NEEDED FOR STABILITY IS MUCH GREATER THAN THE WALL THICKNESS OF A CYLINDRICAL CHIMNEY. THIS INDICATES THAT A CYLINDRICAL CHIMNEY IS BETTER THAN A SQUARE CHIMNEY BECAUSE OF THE RADIATION THICKNESS REQUIREMENT. CALCULATIONS FOR STABILITY OF THE SQUARE CHIMNEY AND FOR THE DESIGN OF THE CYLINDRICAL CHIMNEY ARE ON PAGES 5 THROUGH 10.

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CHECK SIDE PLATE STABILITY REFR: APP 13 PARA 13-14 (a)(2)

ASSUME 3/8" THICK SIDE PLATES. $\Rightarrow t_1 = t_2 = 3/8" = 0.375"$ (SAME AS PG 4)

$$\frac{4 S_{mA}}{S_{crA}} + \frac{4 S_{mB}}{S_{crB}} + \frac{S_{bA}}{\left(1 - 2\frac{S_{mA}}{S'_{crA}}\right) 1.5S} + \frac{S_{bB}}{\left(1-2\frac{S_{mB}}{S'_{crB}}\right)1.5S} \leq 1.0$$

$$S_{mA} = \frac{P_e h H}{2(t_1 H + t_2 h)} = \frac{15(12)(12)}{2(0.375(12) + 0.375(12))} = 120$$

$$S_{mB} = \frac{P_e h}{2t_1} = \frac{15(12)}{2(0.375)} = 240$$

$$\frac{L_V}{H} = \frac{35'}{1'} = 35 \Rightarrow J_B = 0.125 \text{ \& } J_A = 0.0375$$
FROM TABLE 13-14(a).

$$S_{bA} = \frac{6 J_A H^2 P_e}{t_1^2} = \frac{6(0.0375)(12)^2(15)}{0.375^2} = 3{,}456$$

$$S_{bB} = \frac{6 J_B H^2 P_e}{t_1^2} = \frac{6(0.125)(12)^2(15)}{0.375^2} = 11{,}520$$

$$S_{crA} = \frac{\pi^2 E_2}{12(1-\nu^2)}\left(\frac{t_1}{H}\right)^2 K_A$$

$$\frac{L_V}{H} = 35 \Rightarrow K_A = 5.5$$

$$\frac{H}{L_V} = \frac{1}{35} = 0.029 \Rightarrow K_B = 15$$

$$\nu = 0.334 \qquad E_2 = 10.3 \times 10^6 \text{ psi}$$

$$S_{crA} = \frac{\pi^2 (10.3\times 10^6)}{12(1-0.334^2)}\left(\frac{0.375}{12}\right)^2 5.5 = 51{,}214$$

$$S_y = 16{,}000 \text{ psi} \qquad S_y/2 = 8{,}000 \text{ psi}$$

$$S_{crA} = 51{,}214 \not\leq S_y/2 = 8{,}000$$

$$\therefore S_{crA} = S_y - S_y^2/4S_{crA}$$

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$$S_{crA} = 16{,}000 - 16{,}000^2/(4 * S_{crA}) = 16{,}000 - (6.4 \times 10^7)/S_{crA}$$

$$S_{crA}^2 = 16{,}000\, S_{crA} - 6.4 \times 10^7$$

$$S_{crA}^2 - 16{,}000\, S_{crA} + 6.4 \times 10^7 = 0$$

SOLVE USING THE QUADRATIC EQUATION.

$a = 1$; $b = -16{,}000$; $c = 6.4 \times 10^7$

$$S_{crA} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} = \frac{16{,}000 \pm \sqrt{16{,}000^2 - 4(1)(6.4 \times 10^7)}}{2(1)}$$

$$S_{crA} = 8{,}000 \text{ psi}$$

$$S_{crB} = \frac{\pi^2 E_2}{12(1-\nu^2)}\left(\frac{t_1}{L_V}\right)^2 K_B$$

$$= \frac{\pi^2 (10.3\times10^6)}{12(1-0.334^2)}\left(\frac{0.375}{35\times12}\right)^2 15 = 114$$

$S_{crB} = 114 \le 8{,}000 = \tfrac{1}{2}S_y \;\therefore\; S_{crB} = 114$

$S'_{crA} = 51{,}214$

$S'_{crB} = 114$

CHECK THE INTERACTION EQUATION:

$$\frac{4(120)}{8{,}000} + \frac{4(240)}{114} + \frac{3{,}456}{\left[1 - 2*\frac{120}{51{,}214}\right]1.5(9{,}800)}$$

$$+ \frac{11{,}520}{\left[1 - 2*\frac{240}{114}\right]1.5(9{,}800)} = 0.06 + 8.42 + 0.23 + (-0.244)$$

NO GOOD

THE TWO CIRCLED TERMS CONTAIN S_{mB}, S_{crB}, S_{bB} & S'_{crB}. FOR A GIVEN L_V, ONLY t_1 CAN BE VARIED TO CHANGE THE VALUES OF S_{mB}, S_{crB}, S_{bB} AND S'_{crB}. NEGLECT THE "A" TERMS AND SOLVE FOR THE VALUE OF t_1 THAT BRINGS THE INTERACTION EQUATION TO UNITY.

$$S_{mB} = \frac{P_e h}{2t_1} = \frac{15(12)}{2\,t_1} = \frac{90}{t_1}$$

$$S_{bB} = \frac{6\,J_B H^2 P_e}{t_1^2} = \frac{6(0.125)(12)^2 15}{t_1^2} = \frac{1620}{t_1^2}$$

$$S_{crB} = S_{crB}' = \frac{\pi^2 E}{12(1-\nu^2)}\left(\frac{t_1^2}{L_V}\right)K_B = \frac{\pi^2(10.3\times10^6)}{12(1-0.334^2)}\,\frac{t_1^2}{(35\times12)^2}\,15$$

$$= 810.8\,t_1^2$$ (ONLY TRUE FOR S_{crB} IF $t_1 \le 3.14''$)

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$$\frac{4\ S_{mB}}{S_{crB}} + \frac{S_{bB}}{\left(1 - 2\ \frac{S_{mB}}{S_{crB}}\right) 1.5\ S} \leq 1.0$$

$$\frac{4\left(\frac{90}{t_1}\right)}{810.8\, t_1^2} + \frac{\frac{1620}{t_1^2}}{\left(1 - \frac{2\left(\frac{90}{t_1}\right)}{810.8\, t_1^2}\right) 1.5\,(9{,}800)} \leq 1.0$$

$$\frac{0.444}{t_1^3} + \frac{\frac{1620}{t_1^2}}{\left(1 - \frac{0.222}{t_1^3}\right) 14{,}700} \leq 1.0$$

FOR $t_1 = 0.875$, INTERACTION EQUATION $= 0.88$ (= 0.95 WITH "A" TERMS INCLUDED)

FOR $t_1 = 0.75$, INTERACTION EQUATION $= 1.47$

CONCLUSIONS:

1) WALL THICKNESS FOR THIS CASE WOULD BE ~ 7/8". THE DESIGN OF AN UNSTAYED, SQUARE CHIMNEY WILL NOT BE UNDERTAKEN IF A CYLINDRICAL CHIMNEY HAS A WALL THICKNESS LESS THAN 7/8".

2) TRY A CYLINDRICAL CHIMNEY.

3) TRY A SQUARE CHIMNEY STAYED AT MIDLENGTH IF A CYLINDRICAL CHIMNEY IS TOO THICK OR IF THE INSULATING VACUUM FOR THE LHe & LN_2 LINES IS ISOLATED FROM THE PRESSURE RELIEF CHANNEL.

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Note on the calculations for the square chimney

The calculations for the square chimney are preliminary because I have two unresolved questions about the design rules in paragraph 13-14 of Appendix 13.

First, equation (6A) is used to calculate the critical buckling stress, ScrA, for a simply-supported plate in uniaxial, uniform compression along its narrow dimension (about 12" in this case) when ScrA is less than Sy/2. Equation (6A) yielded 51,214 psi, which is greater than the Sy/2 value of 8,000 psi. Equation (6B) must be used when (6A) is not applicable, that is, for ScrA greater than Sy/2. Solving equation (6B) with the quadratic equation yielded only one value for ScrA, Sy/2. This seems inconsistent because the equation is defined for use when ScrA is greater than Sy/2. Since this equation yields only one value (assuming I have solved it properly), is it correct? The design of the square chimney is based on ScrA equal to Sy/2.

The second question concerns calculating the critical buckling stress, ScrB, for a simply-supported plate in uniaxial, uniform compression along its long dimension (about 420" in this case). The equations for ScrB are the same equations used to solve for ScrA. I calculated a value of 114 psi for ScrB. This low value occurs because the plate width, 420" in this case, is a squared term in the denominator. The calculated values of ScrA and ScrB indicate that the critical buckling stress for a 12" wide x 420" long plate is much greater than for a 420" wide x 12" long plate. Is this correct for the plates in this type of vessel? Reference 1 notes that buckling strength of a plate is found to be independent of length when the ratio of plate length to width is greater than 5. Paragraph 13-4 (h) states that the design equations in Appendix 13 are based on vessels in which the length to side dimension ratio (aspect ratio) is greater than 4. Also, these design equations are conservatively applicable to vessels of aspect ratio less than 4. Is it too conservative to calculate critical buckling stress ScrB for the side walls of this long, square vessel with the same formula used to calculate ScrA?

I have given these questions regarding the ScrA/ScrB design equations to Chuck Grozis. He will look for answers at his ASME pressure vessel class.

Derivation of the critical buckling stress equation used in Appendix 13 of the ASME Code can be found in reference 2.

The 1989 edition of Roark's Formulas for Stress and Strain book contains formulas for elastic stability of plates and shells in Table 35 on page 684. Equation 1 is used to calculate the critical buckling stress for a rectangular plate under equal uniform compression on the two opposite narrow edges with several manners of support. For a plate with all edges simply supported or for a plate with all edges clamped, equation 1 yields stresses which are lower than the stress calculated with the Appendix 13 equation. Equation 2 considers uniform loads on all four edges of a rectangular plate. The equation applicable to a rectangular plate with all edges clamped, equation 2b, is noted to be most accurate when the plate is nearly square but the accuracy for other dimensions is not stated. Equation 2a is for a rectangular plate with all edges simply supported. It will be solved if it becomes necessary to use a square chimney.

REFERENCES:

1) Alexander Blake, Practical Stress Analysis in Engineering Design, Marcel Dekker, Inc., New York and Basel (1982), pg 87

2) C. L. Dym and I.H. Shames, Solid Mechanics: A Variational Approach, McGraw-Hill, Inc., USA (1973), pg 499

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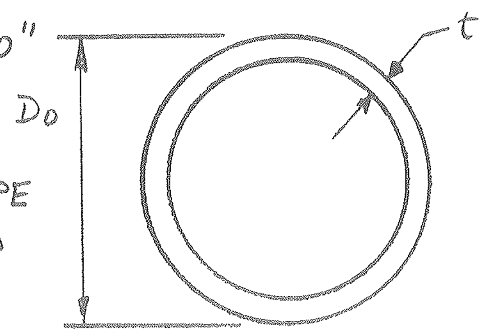
EXTERNAL PRESSURE DESIGN REFR: ASME SEC VIII, DIV I

SET $D_o = 12.75''$

CHIMNEY LENGTH = 35' = 420"

ASSUME $t = 0.25''$ (SCH 20)



MATERIAL: SEAMLESS ALUM PIPE
SB-241 6061-T6 WLD
$S = 6{,}000$ psi

FOLLOW UG-28:

$D_o/t = 12.75/0.25 = 51 > 10$

$L/D_o = 420/12.75 = 32.94$

FROM FIGURE 5-UGO-28.0, $A = 0.00045$

FROM FIGURE 5-UNF-28.30, $B = 2{,}250$

$$P_a = \frac{4B}{3(D_o/t)} = \frac{4(2{,}250)}{3(51)} = 58.8 \text{ psi} > 15 \text{ psi} \quad \underline{OK}$$

REDUCE WALL THICKNESS TO 0.18" (SCH 10)

ASSUME $t = 0.18''$ $R_i = [12.75'' - 2(0.18'')]/2 = 6.195''$

$D_o/t = 12.75/0.18 = 70.8$

$A = 0.00027$

$$P_a = \frac{2AE}{3(D_o/t)} = \frac{2(0.00027)(10.0 \times 10^6)}{3(70.8)} = 25.4 \text{ psi} > 15 \text{ psi} \quad \underline{OK}$$

CALCULATE INTERNAL PRESSURE RATING FOR 0.18" WALL THK

$$P = \frac{SEt}{R + 0.6t} = \frac{6{,}000(1)(0.18)}{\left(\frac{12.75}{2} - 0.18\right) + 0.6(0.18)} = 170 \text{ psi}$$

CHECK LIMITS: $t = 0.18'' < 6.195/2 = 3.0975'' = R_i$ $\underline{OK}$
$P = 170 < 0.385\, SE = 0.385\,(6{,}000)(1) = 2{,}310$ $\underline{OK}$
CIRCUMFERENTIAL STRESS LIMITS P.

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CHECK COLUMN STABILITY FOR AXIAL COMPRESSION ONLY:

$S_y = 35{,}000$ psi

$$C_c = \sqrt{\frac{2\pi^2 E}{S_y}} = \sqrt{\frac{2\pi^2 (10 \times 10^6)}{35{,}000}} = 75$$

$$\frac{2L}{R} = \frac{2(420'')}{(12.75''/2)} = 132$$

$$\frac{2L}{R} = 132 > C_c = 75$$

$$\therefore \quad F_a = \frac{12\pi^2 E}{23(2L_v/R)^2} = \frac{12\pi^2(10 \times 10^6)}{23(132)^2} = 2{,}955 \text{ psi}$$

$$S_a = \frac{P}{A} = \frac{15\ \frac{\text{lbf}}{\text{in}^2} * \left(\pi \frac{(12.75)^2}{4}\ \text{in}^2\right)}{\frac{\pi}{4}\left[(12.75)^2 - (12.75 - 2\{0.18\})^2\right]} = 270 \text{ psi}$$

$$\frac{S_a}{F_a} = \frac{270}{2{,}955} = 0.09 < 1.0 \quad \underline{\text{OK}}$$

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CALCULATE THE CRITICAL COLLAPSING PRESSURE FOR THE CHIMNEY...

REFR: 1) THE NEW-TYPE CODE CHART FOR THE DESIGN OF VESSELS UNDER EXTERNAL PRESSURE.
BY: E.O. BERGMAN
ASME TRANSACTIONS, 1952

2) VESSELS UNDER EXTERNAL PRESSURE
BY: D.F. WINDENBURG
MECHANICAL ENGINEERING, 1937

3) COLLAPSE BY INSTABILITY OF THIN CYLINDRICAL SHELLS UNDER EXTERNAL PRESSURE
BY: D.F. WINDENBURG & C. TRILLING
ASME TRANSACTIONS, 1934

ASME SECTION VIII DIV I USES THE FOLLOWING COLLAPSE PRESSURE FORMULAS IN THEIR METHOD FOR CALCULATING THE THICKNESS OF SHELLS AND TUBES UNDER EXTERNAL PRESSURE (REFR 1):

FOR INSTABILITY FAILURE BELOW THE CRITICAL LENGTH —

$$P_{C_B} = \frac{2.42E}{(1-\mu^2)^{3/4}} \frac{(t/D)^{2.5}}{(L/D) - 0.45(t/D)^{0.5}}$$

FOR $\mu = 0.3$ (μ IS POISSON'S RATIO)

$$P_C = 2.6E\,(t/D)^{2.5} / [(L/D) - 0.45\,(t/D)^{0.5}]$$

FOR 5083-O ALUMINUM AT THE DESIGN CONDITIONS OF THIS CHIMNEY, $\mu = 0.334$. WITH $\mu = 0.334$ INSTEAD OF 0.3, THE CONSTANT IN THE ABOVE EQUATION IS 2.64 INSTEAD OF 2.6. THIS IS A NEGLIGIBLE DIFFERENCE.

THE ABOVE FORMULA APPEARS AS THE COLLAPSE PRESSURE FORMULA IN CGA-341-1987, PG 6.

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- FOR INSTABILITY FAILURE ABOVE THE CRITICAL LENGTH -

$$P_{C_A} = \frac{2.2\,E}{1.27}\left(\frac{t}{D}\right)^3 \quad \text{FOR } \mu = 0.3 \text{ \& } t/D < 0.023$$

FOR THIS CHIMNEY, $t/D = 0.18/12.75 = 0.0141 < 0.023$ OK

THE CRITICAL LENGTH, L_C, CAN BE DETERMINED BY SETTING $P_{CB} = P_{CA}$.

$$\frac{2.6\,\cancel{E}\,\cancel{(t/D)^{2.5}}}{\left[(L_C/D) - 0.45\,(t/D)^{0.5}\right]} = \frac{2.2\,\cancel{E}}{1.27}\left(\frac{t}{D}\right)^{\cancel{3}\,0.5}$$

$$\frac{2.6\,(1.27)}{2.2\,(t/D)^{0.5}} + 0.45\left(\frac{t}{D}\right)^{0.5} = L_C/D$$

$$\frac{2.6\,(1.27)}{2.2\,(0.18/12.75)^{0.5}} + 0.45\left(\frac{0.18}{12.75}\right)^{0.5} = L_C/12.75 \Rightarrow L_C = 162''$$

CHIMNEY LENGTH $= 420'' > 162''$

$$\therefore\ P_{C_A} = \frac{2.2\,(10 \times 10^6)}{1.27}\left(\frac{0.18}{12.75}\right)^3 = \underline{48.74\ \text{psi}}$$

FOLLOWING CGA-341-1987 PARA 3.6.2, THE MINIMUM COLLAPSING PRESSURE OF 48.74 PSI DIFFERENTIAL IS EQUIVALENT TO A 24.37 PSI DIFFERENTIAL PRESSURE WITH A SAFETY FACTOR OF 2.

THE ALLOWABLE EXTERNAL PRESSURE CALCULATED BY THE RULES OF ASME SECTION VIII DIV 1 ON PAGE 9 OF THESE CALCULATIONS IS 25.4 PSI.

$25.4 \doteq 24.37 \Rightarrow$ ASME SECTION VIII DIV 1 HAS A SAFETY FACTOR OF 2 ON COLLAPSE PRESSURE.

THIS CHIMNEY HAS A COLLAPSE PRESSURE SAFETY FACTOR OF $\frac{48.74}{15} = 3.25$.

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DETERMINE THE CIRCUMFERENTIAL STRESS AT THE COLLAPSE PRESSURE:

$$P = \frac{SEt}{R+0.6t} \Rightarrow S = \frac{P(R+0.6t)}{Et}$$

$$S = 25.4\ \frac{(6.195+0.6(0.18))}{(1)(0.18)} = 890\ psi < \text{MATERIAL PROPORTIONAL LIMIT}$$

OK

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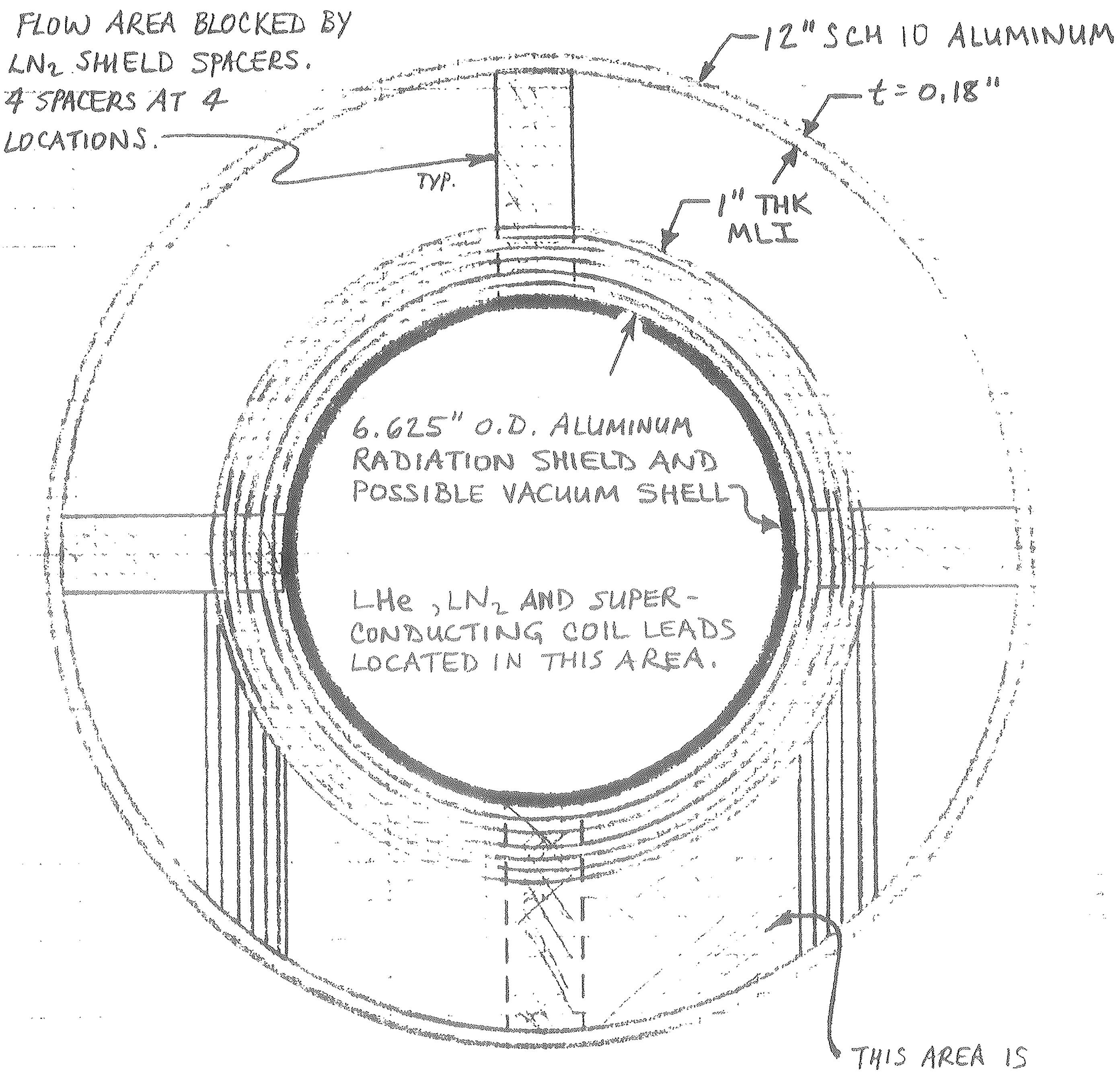

NOTE: THE MLI SHALL BE SECURED SO THE VENTING GAS WILL NOT RIP IT OFF THE LN_2 SHIELD. FOR EXAMPLE, WRAP THE MLI WITH A FABRIC, I.E. NYLON, COVER SHEET AND SECURE THE FABRIC WITH NYLON OR STEEL (CHICKEN WIRE TYPE) MESH, OR ENCLOSE THE MLI WITH A THIN ALUMINUM JACKET.

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PLAN

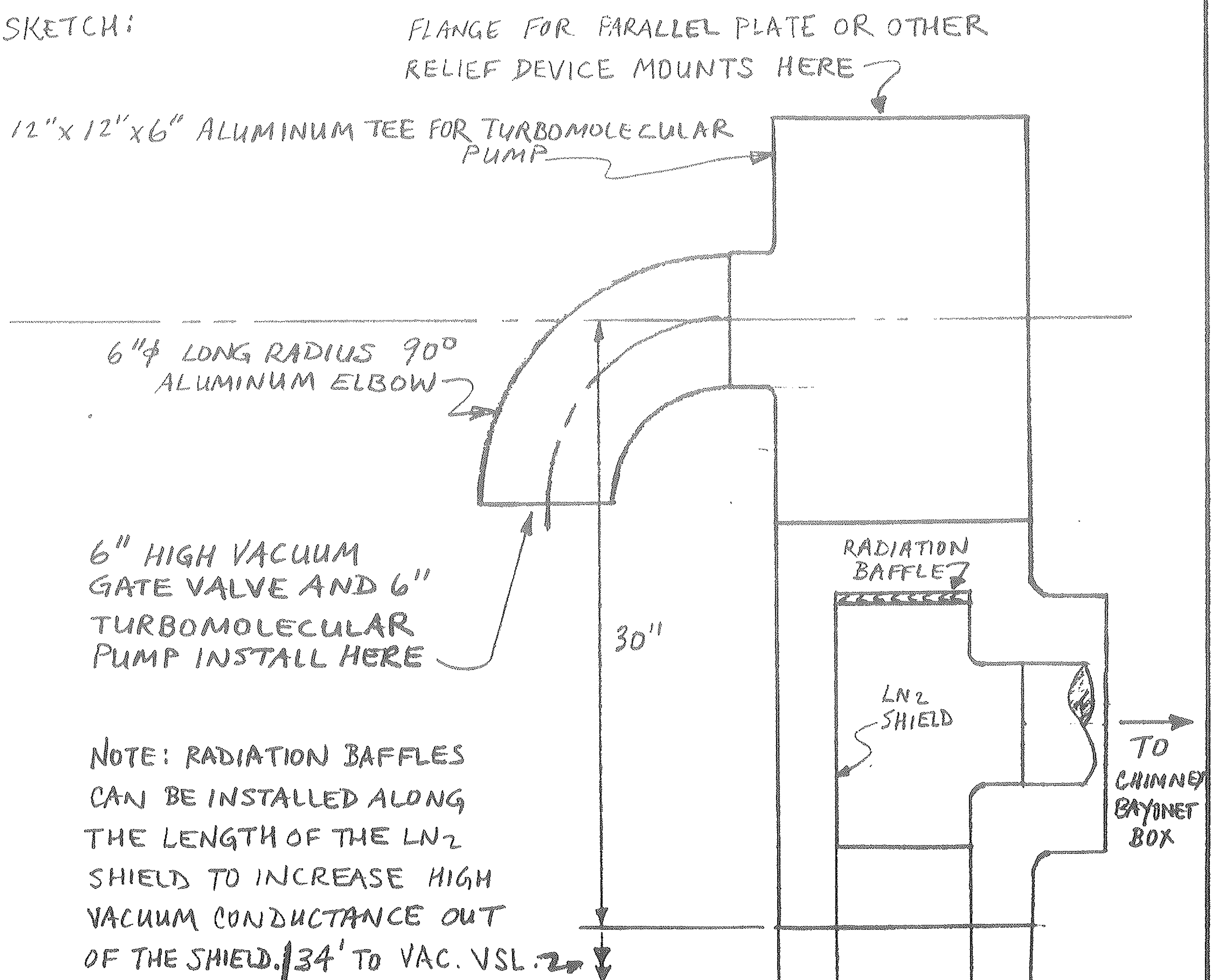
CHIMNEY LENGTH THROUGH THE DETECTOR $= 11{,}315 - \frac{2200}{2} = 10{,}215$ mm

$= 33.5$ ft

ASSUME THE CHIMNEY EXTENDS 6" PAST THE DETECTOR BEFORE THE TEE IS ATTACHED.

$\therefore$ STRAIGHT PIPE LENGTH $= 33.5' + 0.5'$
$= 34'$

SKETCH:



NOTE: RADIATION BAFFLES CAN BE INSTALLED ALONG THE LENGTH OF THE LN_2 SHIELD TO INCREASE HIGH VACUUM CONDUCTANCE OUT OF THE SHIELD.

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